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A program of basic research was carried out, whose objective was to make the promising qualitative thermal wave imaging NDI technique a truly quantitative tool which can have a major impact on the rapid, wide-area inspection of Air Force aircraft for hidden corrosion in aircraft components. During the program a theoretical framework was developed, based on three-dimensional scattering of thermal waves from planar subsurface defects, and the model was used to predict the images of circular sub-surface defects of various radii, located at various depths from the surface of the metal. Experimental measurements on such model structures confirmed the validity of the theory and determined the parameters for applying the technique to the imaging of hidden corrosion in aircraft components. Preliminary testing of the technique was carried out on an aircraft, with corrosion being successfully imaged. Outstanding technical issues include the effects of corrosion products and other realistic thermal boundaries which are encountered in actual aircraft structures, and the development of quantitative corrosion loss estimation algorithms.

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THERMAL WAVE IMAGING OF HIDDEN CORROSION IN AIRCRAFT COMPONENTS

FINAL TECHNICAL REPORT

R.L. THOMAS, L.D. FAVRO AND P.K. KUO

NOVEMBER 22, 1996

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WAYNE STATE UNIVERSITY

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Thermal Wave Imaging of Hidden Corrosion in Aircraft Components
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FINAL TECHNICAL REPORT

ABSTRACT

A program of basic research was carried out, whose objective was to make the promising qualitative thermal wave imaging NDI technique a truly quantitative tool which can have a major impact on the rapid, wide-area inspection of Air Force aircraft for hidden corrosion in aircraft components. During the program a theoretical framework was developed, based on three-dimensional scattering of thermal waves from planar subsurface defects, and the model was used to predict the images of circular sub-surface defects of various radii, located at various depths from the surface of the metal. Experimental measurements on such model structures confirmed the validity of the theory and determined the parameters for applying the technique to the imaging of hidden corrosion in aircraft components. Preliminary testing of the technique was carried out on an aircraft, with corrosion being successfully imaged. Outstanding technical issues include the effects of corrosion products and other realistic thermal boundaries which are encountered in actual aircraft structures, and the development of quantitative corrosion loss estimation algorithms.

Description of the AFOSR/URI-Sponsored Research Program

We proposed a three-year, cost-sharing research program on thermal wave imaging for NDE of hidden corrosion in aircraft components. This proposal was submitted in response to the AFOSR portion of the FY 93 DoD University Research Initiative Research Initiation Program.

The Co-PI's had previously demonstrated the potential of Thermal Wave IR Imaging for NDE of hidden corrosion as one project which has been funded under the FAA-Center for Aviation Systems Reliability. During the course of that project, experience had been gained from imaging of fabricated corrosion test specimens (supplied by Lockheed), on test coupons sectioned from military aircraft (both in collaboration with Lockheed, and as part of the Air Force's ARINC/OC-ALC demonstration test program), and on a B727 aircraft in a civilian airline maintenance hanger. During the course of these feasibility studies for the FAA, a number of important basic research issues emerged, which we proposed to address in this URI research program. In particular, we proposed to exploit an InSb focal plane array imaging system to study the pulse-echo imaging of aircraft components on much shorter time scales than are possible with conventional scanned imagers. As support for our experimental studies, we proposed to carry out corresponding theoretical and numerical analyses of pulsed heat flow in such structures.

Technical Background on Thermal Wave Imaging

The Co-PI's pioneered the development of thermal wave imaging as a nondestructive evaluation (NDE) method. They published the first paper on the subject in 1978[1]. However, it wasn't until the mid- to late-'80's, when infrared (IR) video cameras were first applied to study time-dependent thermal effects, that thermal wave imaging became viable as a general purpose NDE tool. The advantage of an IR video camera is that it provides a fast, real-time, wide-area, record of the time-dependent surface temperature of a sample, making it possible to see returning thermal wave echoes as images on a video monitor. Our research group has continued to be the leader in this area of research by developing techniques for doing synchronous video imaging of defect-induced surface temperature variations, both in the periodic regime, using video lock-in imaging[2], and in the pulsed regime[3], using gated imaging.

The pulse-echo thermal wave imaging system, which was developed by Wayne State University[4], consists of a pulsed heat source (typically high-power photographic flash lamps), an IR video camera, and image processing hardware and software, all of which is controlled by a personal computer. A photograph of a commercial version[5] of this system is given in Fig 1. The heat source in this system is a pair of linear photoflash lamps, designed specifically for this purpose. Each of these lamps is capable of putting out a 6.4kJ pulse of approximately 4ms duration. These lamps are enclosed in an aluminum shroud to trap the light and direct it toward the aircraft. Each lamp is powered by its own capacitor power supply. These power supplies, together with the laptop computer which controls the system, are mounted on a two-wheeled cart, as shown in Fig. 1. The aluminum shroud, shown mounted on top of the cart in Fig. 1, carries the camera and the flash lamps. In use, this shroud is removed from the cart and pressed against the area of the aircraft to be examined. If the aluminum skin of the aircraft is unpainted, it is an extremely good reflector of visible light, and also an extremely poor emitter of infrared radiation, so that the area of the aircraft to be examined needs to be covered with a suitable absorbing and emitting layer. This may either be a water soluble paint or a thin film of some other material which can be readily removed from the surface.

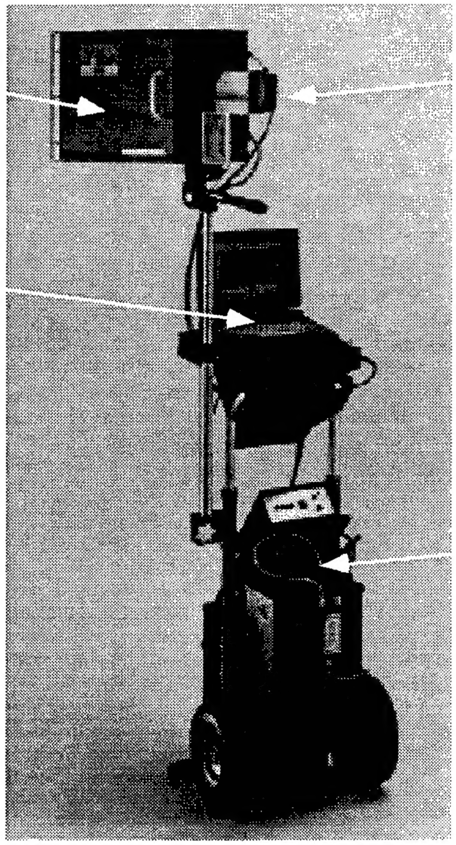

Fig. 1. A commercial version of a pulse-echo thermal wave imaging system, suitable for use in a hangar environment.

The energy from the pulsed flashlamps is absorbed at the surface of the aircraft, and launches a thermal wave pulse into its skin. When this pulse is reflected, either from the rear surface of the skin or from a locally corroded interface, the reflected portion propagates back to the surface, where it modifies the time dependence of the temperature. The modification is greater over a corroded region than over an uncorroded one. Time delays of the reflected pulses are determined by the thermal wave transit times to the defect and back. These transit times to the rear of the skin and back are shorter for corroded (thinner) skin than for the uncorroded skin. The returning thermal wave reflections are detected by means of the IR video camera, which monitors the time-dependent surface distribution of the IR emission from the surface. The signal from the camera is processed in real time by fast imaging hardware and software in the computer, and the thermal wave image of subsurface corrosion is displayed on a video monitor. An example sequence of time-gated thermal wave images of corrosion is shown in Fig. 2.

This figure shows rear surface corrosion of the skin of a B737 aircraft in the FAA's Aging Aircraft Nondestructive Inspection Validation Center (AANC) in Albuquerque. There is a large area of corrosion just above the lapsplice and to the right of the frame station/tear strap. Also, just below the lower left corner of this corroded skin, some additional, smaller, areas of corrosion are clearly seen inside the lapsplice. As time progresses, the large corroded area remains visible, though increasingly blurred and faint, whereas the indications of the smaller areas disappear very quickly. This disappearance is the combined result of three-dimensional heat flow and propagation of heat into the additional layers beneath the outer skin in the lapsplice. It is evident that the most reliable information about corrosion is available only at early times, and that techniques which rely on long-term variations in surface temperature will miss such localized regions of corrosion. Furthermore, any method which attempts to measure loss of skin thickness quantitatively must use the short time information, when the signal strength is independent of the size of the corroded area and any internal structure which may be present.

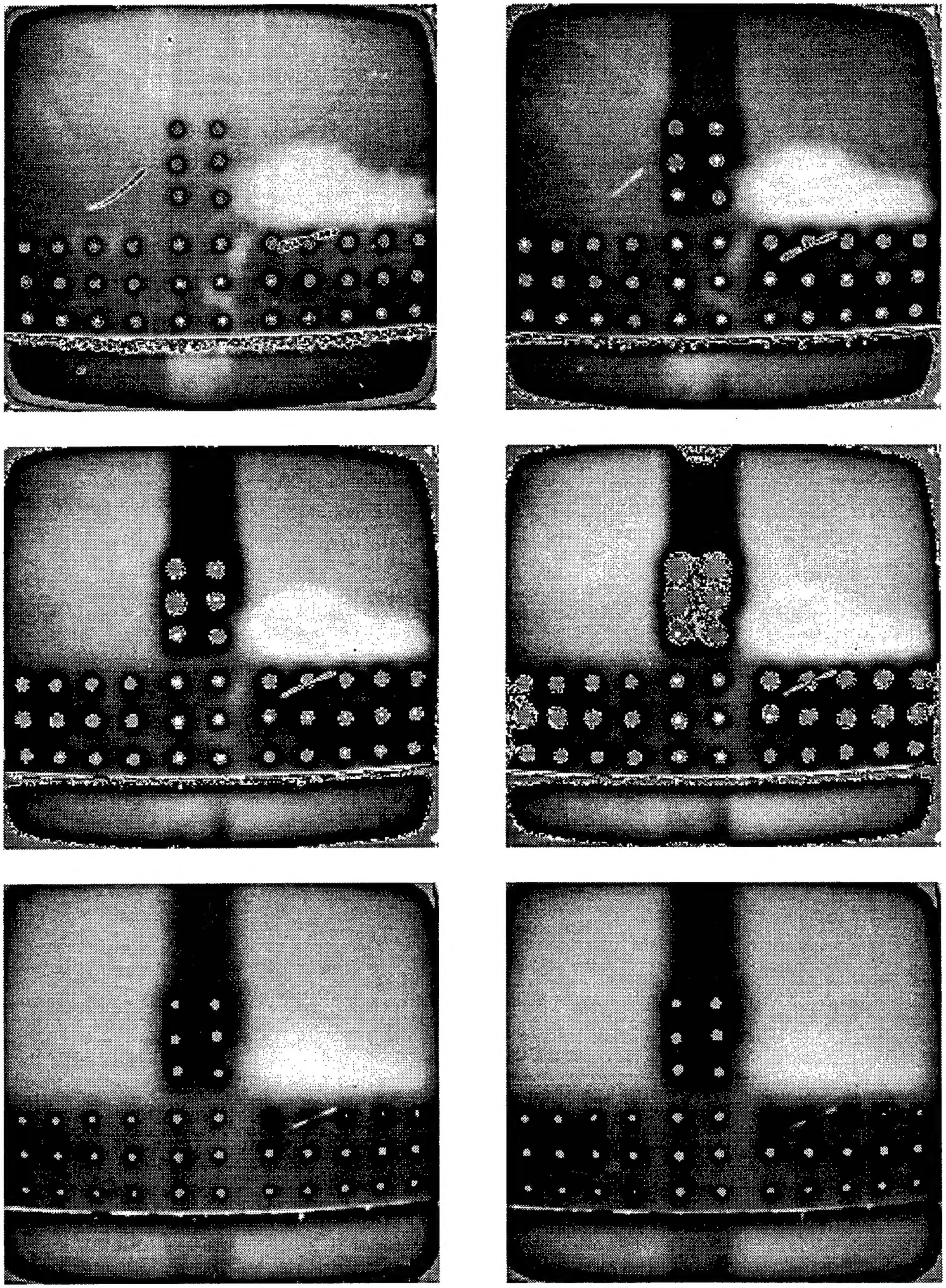

Fig. 2 Sequence of thermal wave images of corroded (bright areas) regions on the B737 testbed in the FAA's Aging Aircraft Nondestructive Inspection Validation Center (AANC) in Albuquerque. The images correspond to progressively later gate times, starting from the upper left (earliest) to the lower right (latest).

It is instructive to estimate the time scales involved in imaging aircraft skin. If one assumes a thermal diffusivity of about 0.5 cm^2/s for an aluminum alloy, and a skin thickness of the order of 1 mm (40 mils), the characteristic diffusion time (the square of the thickness divided by the diffusivity) is 20 ms. Consequently, "echo-ranging" to determine the thickness of a possibly corroded skin requires careful attention (both theoretically and experimentally) to the short-time behavior of the thermal wave propagation. The situation is further complicated by the complexity of the subsurface structure - e.g., the presence of corrosion products, water inside a lap splice, skin which may or may not be adhesively bonded to another layer, etc.

Pulsed thermal waves result from the sudden application of a short pulse of heat to the surface of a solid object. This launches what is, in effect, a temperature wave into the solid. When observed at a distance, x, beneath a planar surface of the object, the pulse has a Gaussian shape given by

$$T(x,t) = \frac{A}{(4\pi\alpha t)^{1/2}} e^{-\frac{x^2}{4\alpha t}} \quad , \tag{1}$$

where T is the temperature, t is the time, α is the thermal diffusivity of the object, and A is a proportionality constant which depends on the heat input. At a defect interface, a second (reflected) pulse is generated with the same Gaussian shape, but with an amplitude which depends on the reflection coefficient at the interface. The reflection coefficient is a function of the ratios of the thermal properties on the two sides of the interface, and can be either positive or negative. The reflected pulse appears to have originated at the image of the object surface, as seen in the "mirror" of the defect interface. Thus, it looks like a thermal wave "echo" from that interface. When it reaches the surface (x=0), it modifies the time-dependence of the surface temperature by contributing an additional term to the inverse square root of time behavior of Eq. (1) at x=0:

$$T(0,t) = \frac{A}{(4\pi\alpha t)^{1/2}}\left(1 + Re^{-\frac{(2d)^2}{4\alpha t}}\right). \tag{2}$$

Here, d is the depth of the defect, and R is the reflection coefficient. The time at which the additional term in Eq. (2) becomes significant depends on d^2/α. Thus, one can, in principle, measure the depth (e.g., thickness of a corroded skin) by observing the time at which the deviation from Eq. (1) occurs. However, this measurement is complicated by variations in the (unknown) value of R, and by the effects of three-dimensional diffusion, which have been ignored in this simplified one-dimensional picture. Also, if one waits a bit longer, one gets additional terms in Eq. (2), due to multiple reflections of the pulse. It should also be kept in mind that thermal waves are extremely dispersive, so that the pulses broaden dramatically as time progresses, and the multiple "echoes" all overlap. Nevertheless, if the surface temperature is observed at short enough times after the flash, one can essentially eliminate the effects of both multiple reflections and three-dimensional diffusion, and make a determination of the "time-of-flight".

Results of the AFOSR/URI-Sponsored Research

A. Theory

During the course of our research, we have developed a mathematical model[6] based on three-dimensional wave scattering theory, which accurately predicts the temperature-time profiles at a given point, and also predicts the variations of the temperature on the surface above an arbitrarily-shaped defect. This theory has been used to calculate theoretical images of defects with several simple geometries in steel and composite materials, and has been confirmed by comparison with experimental thermal wave images of corresponding test specimens. We even have been able to use the wave scattering theory to do inverse scattering calculations, and thus determine the exact size and shape of a subsurface scatterer using only the data in a single thermal wave image from the surface of the object.

The three-dimensional thermal wave diffraction from a subsurface planar scatterer of arbitrary shape, f (x',y'), in a thermally anisotropic material, can be written as

$$\Delta T = \frac{-1}{2\pi}\left(\frac{1}{\pi\alpha_1\alpha_2\alpha_3 t}\right)^{1/2} \iint dx'\, dy'\, f(x',y') \sum_{m=1}^{\infty} \frac{R^m}{A_m} \frac{1}{\alpha_3^{1/2}} \left[\frac{\partial}{\partial z} e^{-\frac{\left[A_m + \left(z^2/\alpha_3\right)^{1/2}\right]^2}{4t}}\right]_{z=\ell}, \tag{3}$$

where f(x',y') describes the shape of the scatterer,

$$A_m = \left[\frac{(x-x')^2}{\alpha_1} + \frac{(y-y')^2}{\alpha_2} + \frac{(2m-1)^2 \ell^2}{\alpha_3}\right]^{1/2}, \tag{4}$$

$$R = \frac{1-e}{1+e}, \text{ and where } e = \sqrt{\frac{(\kappa\rho c)_2}{(\kappa\rho c)_1}}\ . \tag{5}$$

In Eqs. (3) and (4), α_i are the components of the anisotropic thermal diffusivity of the material, and t is the time after the flash at which the image is acquired. The summation over the index, m, takes into account multiple reflections of the thermal wave pulse between the subsurface scatterer and the surface of the material. Such reflections are increasingly important when the lateral dimensions of the subsurface scatterer become large, or when the scatterer is close to the surface.

B. Experiment

Figure 3 shows schematic diagrams of two steel flat-bottomed hole specimens used to test the predictions of Eq. (3). One of the specimens has six holes, each 19mm in diameter, milled into the rear surface of the sample. The flat bottoms of these holes are 1 - 5 mm beneath the painted front surface. The other specimen has five milled holes of diameters ranging from 6 mm to 50 mm, all located at the same depth, 1.2 mm. Figure 4 is a schematic representation of the predictions of Eq. (3), and indicates two characteristic features, the peak contrast time and the peak slope time, which we have used to produce both theoretical and experimental images of the samples shown in Fig. 3. The purpose of using these features is to determine their reliability for measuring the depths of such holes, independently of their lateral sizes.

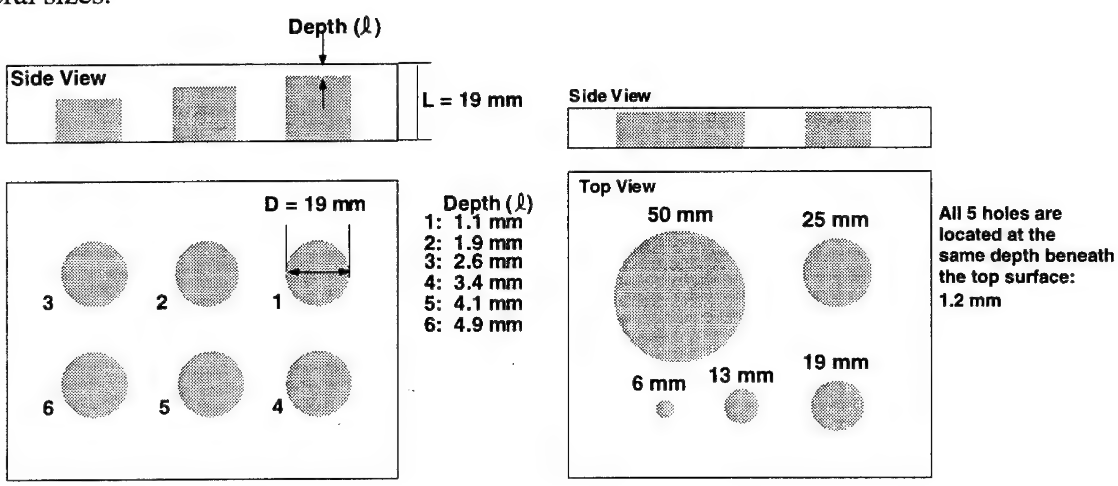

Fig. 3 Schematic diagram of two flat-bottomed hole specimens used to test the predictions of Eq. (1).

Using Eq. (3), we have calculated the peak contrast time (see Fig. 4) at every point on the surfaces of the two samples shown schematically in Fig. 3.[7] The result of this calculation shows that for the six-hole sample, with varying defect depths, the peak contrast times over the centers of the holes vary as the square of the depth. This result was confirmed by experimental imaging of the six-hole sample. By itself, this would seem to indicate that one could use the peak contrast time to measure the depth of a defect, and thus, this parameter could be used to measure the skin thickness over a corroded area on an aircraft. However, similar calculations and experimental measurements on the five-hole sample (where

all of the defects are at the same depth, but have drastically different lateral dimensions) reveal that the peak-contrast times over the center of these holes are a strong function of the size of the holes. This dependence is shown graphically in Fig. 5, and results from the effects of multiple thermal wave reflections, which are more pronounced as the size increases. The strong dependence on lateral defect size makes it difficult to get any simple algorithm which would give the defect depth (degree of

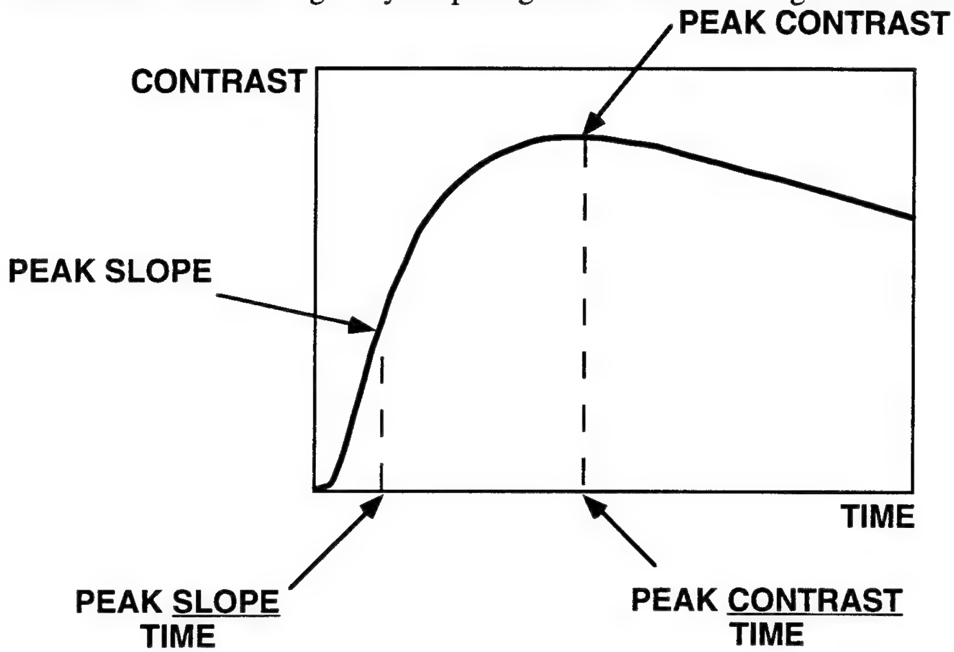

Fig. 4 Sketch of a typical thermal wave contrast curve (the surface temperature over the defect minus the surface temperature over a background region) as a function of time. The times indicated are possible candidates for making depth measurements.

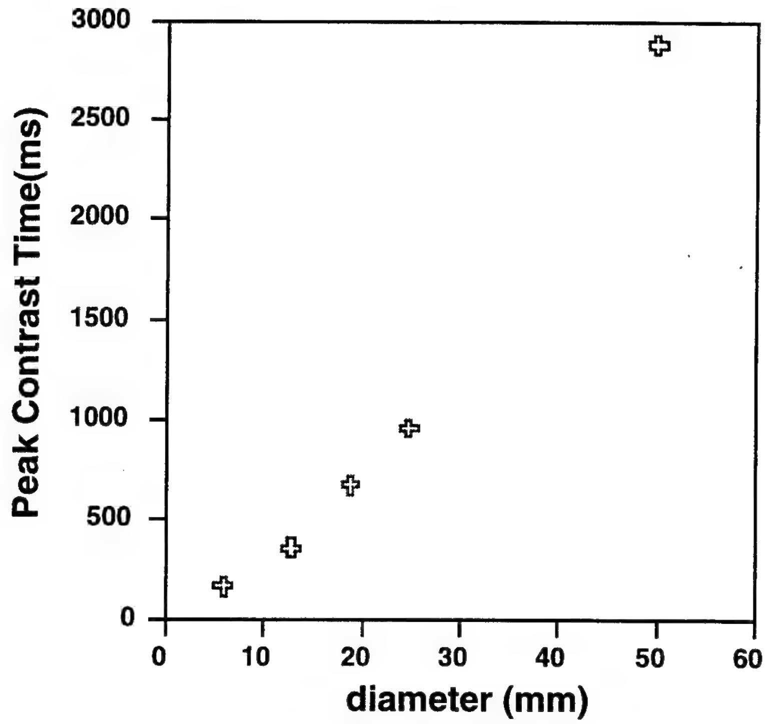

Fig. 5 Peak contrast time over the centers of the five holes of constant depth, shown as a function of the diameter of the holes. Note that the peak contrast time depends very strongly on the lateral size of the defect.

corrosion) using this parameter.

The inability of the peak contrast time to discriminate the depth of a defect independently of its size lead us to look for some other feature of the contrast curve which might be used to measure the depth. Since the leading edge of the contrast curve should be almost totally dominated by the first reflection which returns from the defect, we looked for some characteristic feature of the leading edge of the curve which could be used. We selected the peak slope time, shown schematically in Fig. 4, because it could be determined experimentally with a simple algorithm. A test of its dependence upon the depth of the defect is shown in Fig. 6, for the six-hole sample. The plots in Fig. 6 show clearly that the peak slope times increase in proportion to the square of the depth of the holes. The reason for having only four points in the experimental plot of Fig. 6 is that the experiment didn't run long enough to get the two deepest holes. Also, the differences in slope between the theoretical and experimental curves can be attributed to the choice of an incorrect thermal diffusivity value in the theoretical expression. We have further confirmed the independence of the peak slope time on the lateral size at constant depth, again

using the five-hole test sample, as shown in Fig. 7. It can be seen from the theoretical and experimental plots that the peak slope time is independent of the lateral size of the defect, making the peak slope time the parameter of choice for depth measurements.

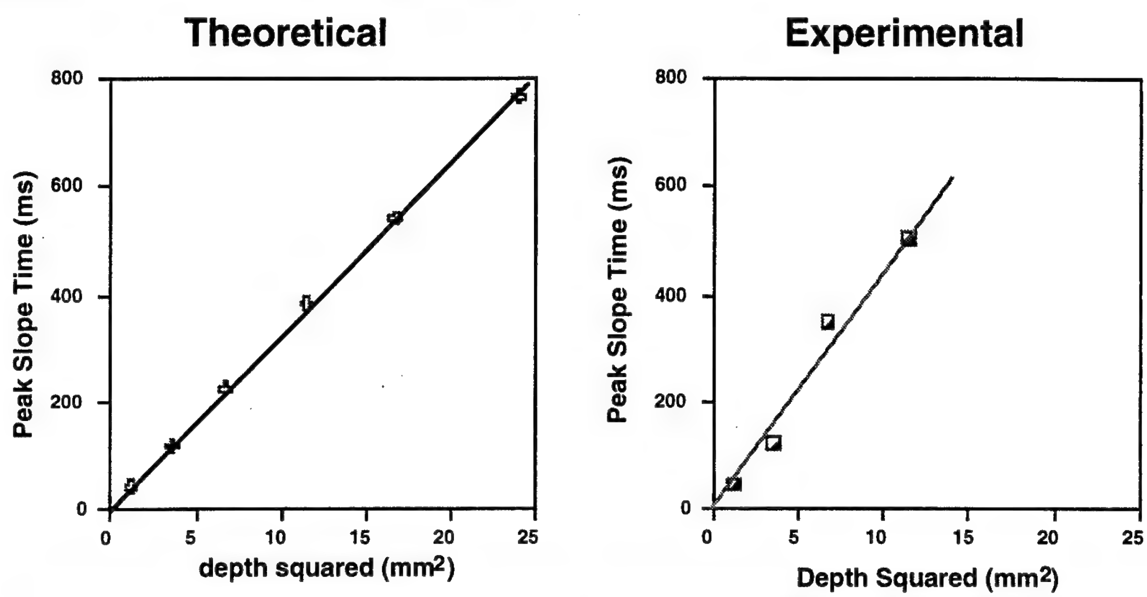

Fig. 6 Theoretical and experimental plots showing the depth-dependence of the peak slope time above the centers of the six-hole test specimen of Fig. 3. The experimental data did not extend long enough in time to detect the two deepest holes.

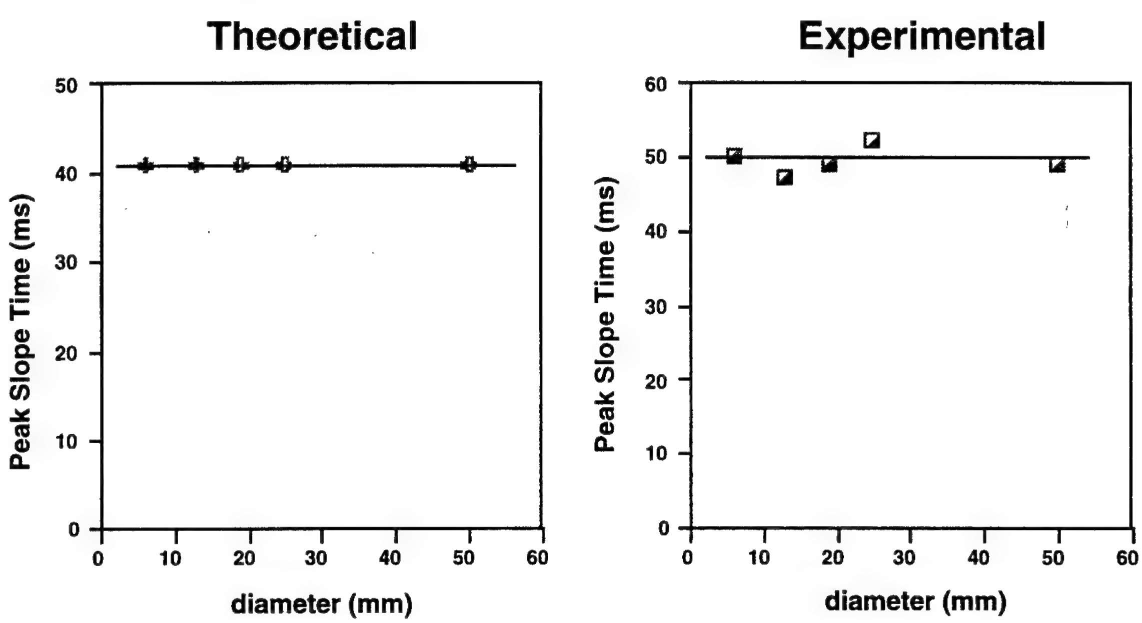

Fig. 7 Theoretical and experimental plots of the peak slope times for the five-hole sample shown schematically in Fig. 3. These plots show the diameter-dependence of the peak slope time above the centers of the holes.

The experiments and theory developed under the AFOSR/URI-Sponsored Contract, as

summarized above, show that the early-time thermal wave contrast contains reliable information about the depth of the defect. We have also carried out these experiments and calculations for the case of changed subsurface boundary conditions. Experimentally this was done by filling the holes with different materials, e.g., water. In this way, we have been able to change the reflection coefficient in Eq. (5) from a value of +1, corresponding to air beneath the metal, to values less than one, and in some cases to negative values. These results are all consistent with the predictions of the theoretical model.

Outstanding Issues

It should be noted that in our current work, the test specimens have been fabricated from steel, rather than aluminum, primarily because of the limitations on imaging speed for the IR cameras used in the measurements described above. Also, the theoretical model used is one in which the time duration of the heat pulse is assumed to be small compared to the thermal wave transit times down to the defect and back. This approximation is quite reasonable for our steel specimens, whose defect depths are 1mm or more, but is much poorer for thinner, corroded, aircraft skin, with its greater (perhaps as much as 5 times) thermal diffusivity. Because the minimum pulse length of high-power, reasonably priced commercial flash lamps is restricted to be a significant fraction of the thermal wave transit time in aluminum skin, we have to modify the theoretical model to take account of the finite duration and shape of the pulse. Experiments to determine the duration and shape of the pulse will have to be done with a faster camera than that which has been used in the current work. Fortunately, through an NSF Instrumentation Grant, with matching money from WSU and industry, we have very recently acquired a state-of-the-art camera which is capable of high speed imaging at frame rates up to 34kHz.

Another practical consideration is that an aircraft skin provides no thick background area for determining image contrast. Our test specimens have been fabricated from thick metal (see Fig. 3), which makes a convenient background reference. In an aircraft skin, the reference will have to be the undamaged skin areas, which are of the order of 1mm in thickness. This reference, must then be compared with the corroded areas, which may be only a few percent thinner. Nevertheless, despite the lack of a thick reference, we have succeeded in detecting and imaging corroded regions of aircraft skin quite well (see Fig. 2). To further illustrate the detectability of corrosion on thin material, we have imaged a 1mm aluminum panel with simulated rear-surface corrosion, corresponding to material loss ranging from 50% down to 5%, as shown in Fig. 8, below. Thus, we are confident that excellent potential exists for carrying out quantitative imaging measurements of corrosion on aircraft skins, with a sensitivity which is sufficient for determining 5% material loss, or less.

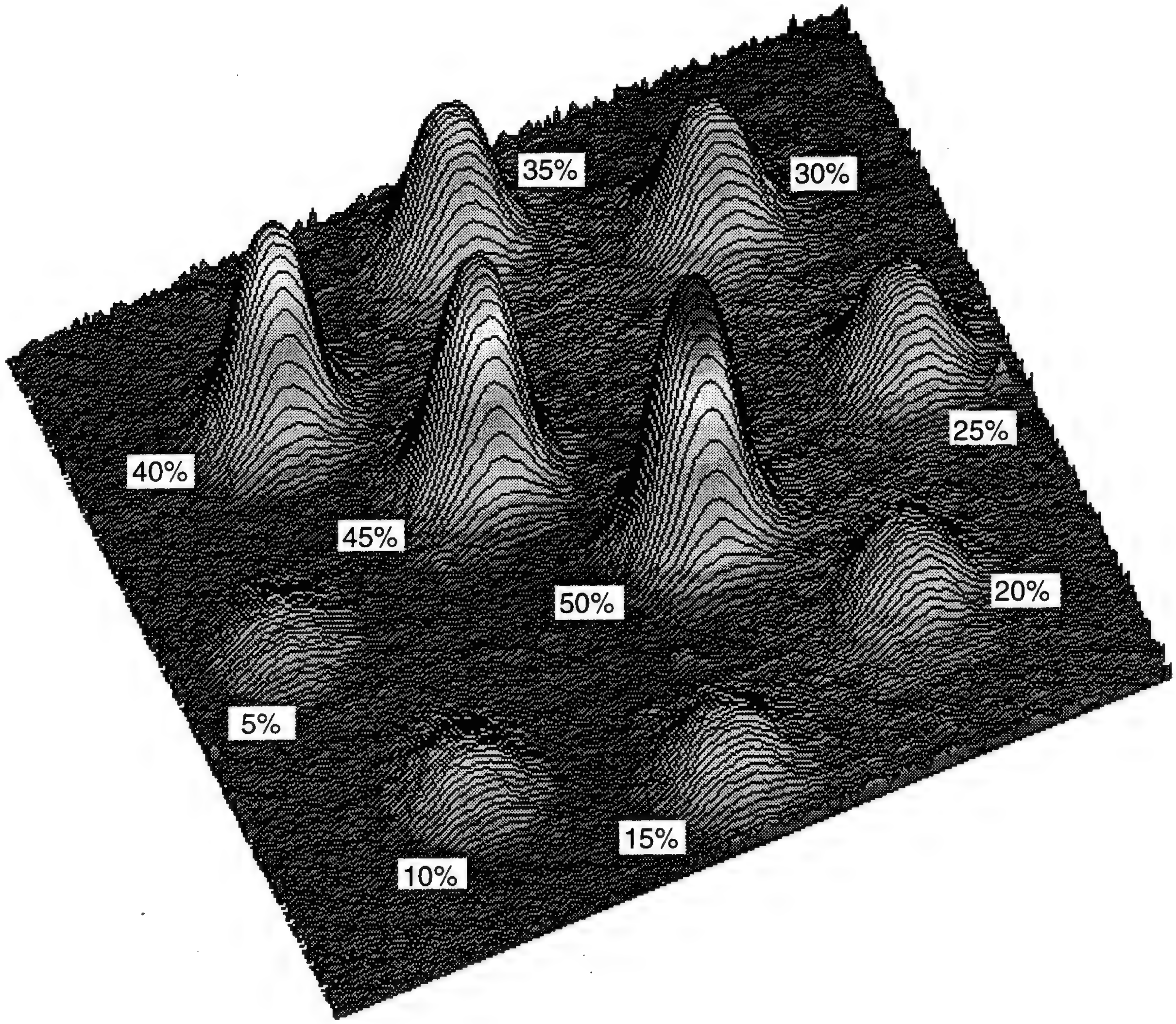

Fig. 8 Thermal wave image of a 1mm aluminum panel with simulated rear-surface corrosion, corresponding to material loss ranging from 50% down to 5%.

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